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NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION 1989 REVIEW AND 1990 WORK PROGRAM

Report No. 90-70-K

B. Mukherjee
Acting Section Head

ABSTRACT

The projects and achievements of the Nondestructive and Fracture Evaluation Section in 1989 are reviewed. Proposed projects and objectives for 1990 are described in outline.

job	file	date	report no.
	826.0	April 12, 1990	90-70-K

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EXECUTIVE SUMMARY

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION 1989 REVIEW AND 1990 WORK PROGRAM

Report No. 90-70-K

B. Mukherjee
Acting Section Head

As for previous years, most of the Nondestructive Evaluation Unit's work was on pressure tubes. New scanning software was written, which the Unit used very successfully at Bruce and Pickering. Similar software was also used on the P4 L20 defect, and on delayed hydride cracks at CRNL. The new laser thermography technique for annulus gas flow measurement was used on Pickering 3, with success. SLAR (Spacer Location And Repositioning) was given support towards its final stages, and an improved SAG module was investigated. A module for the detection of uncracked blisters was successfully developed at the end of the year. A technique for accurately measuring the depths of hydride blister cracks and another technique for sizing defects in pressure tubes using pitch-catch were demonstrated. Eddy current work concentrated on building a garter spring coil for on-power use (Spacer Location At Power, SLAP), finalizing the GAP module, and investigating swept frequency eddy current. A digital signal processing technique was used to demonstrate the feasibility of detecting tight garter springs using normal beam ultrasonics. Other digital signal processing techniques involved deconvolution of signals and filtering. Work continued on measuring hydride concentration, both by eddy current/resistivity and by ultrasonics (primarily differential velocity measurements and nonlinear ultrasonics). A prototype Electro Magnetic Acoustic Transducer (EMAT) system was received for eventual on-power inspection of pressure tubes. For acoustic emission, a spectrum of signals was obtained from a laboratory leaking pressure tube for further analysis by a waveform classifier. In non-pressure tube work, a multi-probe inspection system for steam generators is approaching completion, and a low pressure turbine disk inspection system probe pan was built. The robotic scan of a diffusion bond on a prototype nuclear used fuel container was completed. Lastly, a calliper technique and an EMAT device were developed for measuring the thickness of the Pickering A ring thermal shield support brackets.

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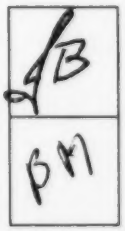
A great deal of work within the Fracture Mechanics Unit was also related to pressure tubes. The first fatigue crack growth rate test was completed in high pressure high temperature water. The test was conducted on a Zr-Nb compact tension specimen at 290°C and 8.4 MPa. The pressure tube burst test facility was used to develop test methods for fracture toughness testing of tubes containing surface cracks and to investigate the criteria for wall penetration by surface cracks grown by delayed hydride cracking. In addition to tube tests a number of small specimen tests were also completed. Materials were prepared with different hydrogen concentrations and various hydride continuity coefficients. Curved compact tension specimens were tested to determine the effects of variation in hydride structure and hydrogen concentration on the fracture toughness of irradiated and unirradiated Zr-Nb. Work has been ongoing to develop a technique for adding hydrogen to samples of Zr-Nb pressure tube by hydrolysis.

A test program was completed to characterize the fracture properties of A212 Gr B steel base and weld metal that were in service at Lakeview TGS. Material for this program was obtained from sections of downcomers from Units 5, 7 and 8 of Lakeview TGS. The fracture properties of hydrogen-blistered steel were evaluated to assist in establishing repair or retirement criteria for hydrogen blistered pressure vessels at the Bruce Heavy Water Plant (BHWP). Results indicated that blisters appeared to have little effect on the material's crack growth resistance. Hydrogen had a marked effect on toughness, reducing the crack growth resistance of hydrogen-charged material threefold at 21°C. Fracture toughness tests were performed on samples prepared from 2.5" Sch 100 A106B feeder pipe at both room temperature and liquid nitrogen temperature (-196°C). These tests were conducted to determine toughness of feeder pipes during an ice-plugging procedure.

Detailed evaluation procedures for the assessment of sharp and blunt flaw indications in a Zr-Nb pressure tube have been further developed. The procedures included crack driving force calculation procedures, notch-tip stress calculation procedures, sub-critical crack growth calculation procedures, and material properties. The evaluation procedures are being developed jointly by Ontario Hydro and AECL. The SLAR operation induces stresses in the Zr-Nb pressure tube which are above normal operating stresses. The effect of SLAR stresses on flaws, including cracked blisters, which may exist in the pressure tube was assessed. This information was used by CPS in assessing the impact of SLAR on flawed pressure tubes, as well as input into determining the inspection requirement of SLAR. Work was also conducted on improving the accuracy of the calculation of critical crack length in pressure tube, on evaluation of fret marks in Bruce Unit 2 and Pickering Unit 3 and on stress relaxation at notches due to creep. The Unit's commitment to the Darlington Leak-Before-Break Program was also completed.



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TO: D. Mills
Director of Research

NONDESTRUCTIVE AND FRACTURE EVALUATION SECTION 1989 REVIEW AND 1990 WORK PROGRAM

I - INTRODUCTION

The highlights of the Section's 1989 work program is in this report, followed by the 1990 work program plan.

Both the Nondestructive Evaluation Unit and the Fracture Mechanics Unit received several major projects and significant funding from the CANDU Owners Group (COG). Currently, a great deal of the Section's longer term work is driven by the COG initiative. Other major projects were in support of plant licensing, operation, in-service inspection and startup of nuclear and thermal plants. These projects were given highest priority due to regulatory and economic considerations. Students and other attached staff played a significant role in carrying the Section's work load. Financially, the Section's Research OM&A expenditure was within the 1989 budget.

Section Personnel

Nondestructive Evaluation

Senior Research Engineer	Dr. M.P. Dolbey

Nondestructive Evaluation Unit

Engineers	Dr. M.D.C. Moles Mr. W.K. Chan Mr. E. de Buda Mr. D.W. Donnelly Mr. J.H. Sedo Mr. S.M. Kramer Mr. D. Mair Mr. M. Grabish* Mr. M. O'Brien

*Attached Staff - CPSD

Technologists	Mr. A.L. Allen Mr. E. Bernacchia Mr. B. Antonacci Mr. J.R. Boon Mr. G.E. Truemner Ms. F.C. Earl Mr. K.C. Watt Mrs. Cecilia DeAraujo**

**Attached Staff - DNGS

The objectives and principal research interests of the Unit are

- Design and Development of remotely operated, electromechanical scanning systems for nondestructive examination of nuclear station components to reduce man-rem expenditure and improve inspection reliability.
- Evaluation of new concepts and development of equipment to enable remote and precise spatial measurements in nuclear power stations.
- Research into limitations of, and applicability of, nondestructive testing techniques for defect detection and evaluation, particularly with regard to nuclear periodic inspection requirements.
- Development of new nondestructive techniques and procedures for particular applications at generating plants and transmission systems.
- Investigation of signal analysis methods for improved defect characterization.
- Assistance to operational groups with non-routine inspection problems, major system breakdowns, and service inspection requirements.

Fracture Mechanics

Engineers	Mr. M.L. Vanderglas Mr. D.A. Scarth Mr. A.C. Wallace Mr. O.E. Lepik Mr. D. Mok
Technologists	Mr. D.W. Carpenter Mr. D.M. McCluskey Mr. J. Schaefer Mr. M. Peixe*

*Student - University of Toronto

The objectives of the Unit are

- Assess the impact of flaws and off-design operation on the reliability and safety of major plant components.

- Propose and evaluate new methodology for flaw-structure interaction analysis that will quantify the real margins of safety of pressure bearing components.

- Improve quantitative understanding of the effects of plant chemistries, materials and fabrication processes and stress state on performance of major plant components.

The main research interests of the Unit are

- Research into experimental and computational aspects of fracture mechanics.

- Determination of fatigue and fracture properties of generating plant and transmission system materials under operating environmental conditions.

- Investigation of techniques for service life prediction of components.

- Development of new fracture mechanics analysis procedures where conventional techniques are inappropriate.

- Development of rapid structural integrity evaluation methods to meet jurisdictional requirements.

II - 1989 WORK PROGRAM REVIEW

1.0 NONDESTRUCTIVE EVALUATION

1.1 NDE Techniques R&D and Applications

Swept Frequency EC

Studies are underway to explore methods of measuring and displaying the frequency dependance of complex impedance variations normally encountered in traditional EC work. The current experimental set-up consists of an HP swept frequency gain-phase analyzer, a wide band floating output drive amplifier and a 386 computer used to control and acquire data from the HP instrument over the IEEE 488 bus. Programs have been written using the ASYST system to perform typical sequences of measurements used to manipulate the resulting data.

Thus far it has been possible to produce plots of the frequency dependance of the air normalized impedance of a probe at any nominal test condition. These plots are often referred to in the EC literature but are usually visualized by referring to simple standard cases or by using a computer model to estimate the plot for specific cases. The new ability to quickly and conveniently obtain this information experimentally is useful for choosing a good inspection frequency and for estimating the probe's impedance behaviour in response to changes in various test conditions.

It has also been possible to measure the change in impedance as a function of frequency between a nominal test condition and a disturbance condition. This data is referenced to the air normalized impedance plane so as not to over emphasize the high frequency response. The resulting data defines a surface which illustrates the frequency dependance of a traditional EC indication. A variety of formatting programs have been written to transfer the data to different graphics programs. An evaluation is ongoing of their capability to display the data in a way that reveals the frequency dependance but still allows the experience provided by traditional EC analysis to be used

Remote Inspection

The robotic inspection of the prototype diffusion bond final closure weld of a used fuel container has been completed. Most of the emphasis has been on improving the accuracy and reliability of the robot. As before, the robot was programmed to map the surface by maximizing the signal amplitudes from an ultrasonic probe/waterjet. This mapping gave container orientation and position. These data were stored in the computer's memory, and used to position the robot for scanning. The prototype diffusion bond ring contained several intentionally embedded defects such as lack of bonding, grease marks and wires. These were reliably detected each scan, with the exception of the smallest wires. Overall, the results show that the robot can be programmed to remotely inspect almost to laboratory standards.

On-Power UT Inspection of Pressure Tubes

A turnkey EMAT system was received from the manufacturer at the beginning of the contract year. As EMAT technology is fundementally different from conventional piezoelectric ultrasound technology, a considerable amount of learning has been required.

Initial attempts were made at setting up the device. This proved difficult due to the large number of tuning variables. However, after some months, most of the nuances of the device had been resolved. A special test tube was made containing only a few notches due to the need to have a clear path round the tube.

Once tuned, attempts were made to reproduce the original readings performed by the manufacturer. Signal amplitudes proved to be much lower than the manufacturer's values, and it was finally concluded that too much wear and tear had damaged all the transducers. Conseqently, the original head was returned to the manufacturer for repair, and a backup head ordered.

Overall, the EMAT device appears to function as specified. However, there are several drawbacks that will need to be addressed. First, the transducers are fragile (0.5 mm titanium sheet faceplate), so will need to be handled with more care. Second, the plate waves generated are very dependant on actual tube wall thickness, and so are very sensitive to frequency. This requires continual adjustment of the signal generator in the lab, which is undesirable in reactor. It should be possible to develop some type of self-tuning device. Lastly, the laboratory head is rather heavy, though this would not be a problem in reactor. None of these problems is insurmountable.

Expert System for Detection of Uncracked Hydride Blisters

The ICEPAK waveform classifier was used to evaluate several blisters using a variety of transducers and incident angles. Initially, the ICEPAK feature extraction system was re-written.

Subsequently, tests were performed using 10 and 20 MHz transducers, 45° and 55° double and single skip modules in pitch-catch.

The results showed that there were significant differences in the waveforms from blisters and parent materials. However, the significant features varied from one transducer/module arrangement to another, though they were consistent within any one transducer/module arrangement. Overall, the expert system could classify unknown signals with over 90% confidence. The results did not depend on the type of classifier algorithm.

Scanning showed a number of features not identifyable with static inspection: 1) there were significant amplitude changes at the edges of the blisters; 2) a small but significant time-shift occurred in the blisters; and 3) there were significant spectral effects at the blister edges. The presence of crack-

ing was not thought to affect the results. Given the progress on the uncracked blister module (below), no further work is recommended on the expert system for this application.

Eddy Current (EC) Amplifier Design for Analysis with HP 4194

A wideband drive amplifier required for use with the HP 4194 Impedance Gain Analyzer is complete. This amplifier boosts the HP 4194 output to +- 20V/400 mA power output. Constant gain and low phase shift are maintained over a range of DC to 10 MHz for swept frequency EC applications. In order to use the amplifier up to 10 MHz, additional shielding methods were utilized including copper tape ground plane, connection of components directly to pins of APEX op amp, and the use of twinax cable for the output connection to the EC probe.

Two Dimensional Filters for Ultrasonic Image Enhancement

A number of two dimensional filters were developed for the enhancement of ultrasonic B and C-scan images. Noise reduction, edge enhancement, and directional enhancement filters were developed and evaluated using test images. A selection of filters has been prepared for incorporation into the current laboratory data acquisition software.

Acoustic Emission Pressure Tube Leak Detection

A high temperature endfitting and pressure tube mock-up has been assembled and tested. Acoustic emission data was collected for various pressures, temperatures and leak flow rates. The intelligent signal classifier hardware and software has been implemented in the laboratory computer system and preliminary testing was begun. The classification of leaking pressure tube signals from laboratory mock-up is underway.

Ultrasonic Garter Spring Detection

Considerable progress has been made in the ultrasonic detection of garter springs. Laboratory work has been completed confirming the effect of a garter spring on the ultrasonic outside surface echo. By using a spatial frequency correlation technique enormous improvements in signal to noise ratio have been achieved. An alternate approach to signal enhancement using bandpass digital filters was also successful in detecting the garter spring signals with a good signal to noise ratio. Either technique requires good coupling between the pressure tube and the garter spring; the typical inservice garter spring compression appears to be sufficient.

Deconvolution and Temporal Leakage

Further work into methods of ultrasonic pulse deconvolution has led to some interesting results concerning the limitations of commonly used methods. Current practice for evaluating deconvolution algorithms concentrates on the effects of noise on the inverse process using simulated delta function sequences. The present work indicates that this approach ignores an important source of potential problems, namely the "temporal leakage" that will occur in all real systems. The effect of this "leakage" is to smear a delta function over the entire time window. One result of this is that a Nyquist rate acquisition may be insufficient when the goal is a temporal deconvolution.

GDCPS Software Package

The Generalized Data Collection and Playback Software (GDCPS) package is being developed within the ND & FE Section to provide a comprehensive software package to satisfy the section's varied data collection, processing, and display requirements. Development of the software began in 1988 but significant enhancements have been added during 1989.

The GDCPS package has been extended to support three new data acquisition products. The Adaptronics PCPR is an ultrasonic pulser/receiver fully contained on a PC board that can be installed directly into a computer. The Adaptronics PCTR is a transient recorder board capable of digitizing at up to 160 MHz via time-equivalent sampling. The Sonotek STR 8100 is a transient recorder board capable of sampling at up to 100 MHz without the need for time-equivalent sampling. Both the PCTR and the STR 8100 are peripheral cards which can be installed directly into a PC.

With the added capabilities of the newly supported hardware, the package's B-scan capabilities had to be enhanced. These enhancements include a new set of data display formats which can generate an isometric presentation of collected data. Digital signal processing options have been extended to include an FFT capability which is used primarily for characterizing ultrasonic transducers. Graphics hardcopy may now be produced on a HP Paintjet printer as well as on a Shinko thermal transfer printer.

The GDCPS package was brought to the field twice in 1989 to complement the capabilities of the CIGAR data acquisition system. In both instances, GDCPS was instrumental in obtaining the information necessary to bring a reactor unit back on-line. As a result, CPS has asked that GDCPS be included as a permanent component in the CIGAR system. This required some modifications to the software package and also to the CIGAR hardware to provide complete compatibility. These modifications are progressing well and should be complete within the first quarter of 1990.

In 1989, it was undertaken to re-develop the GDCPS package in the Microsoft Windows operating environment. This environment provides a superior platform from the point of view of a sophisticated, graphics oriented operator interface and a more extendible software package. The new version of GDCPS will be vastly superior to the current version in terms of capabilities and overall design. The first working GDCPS package for Windows should be ready by mid 1990.

1.2 Inspection System Developments

COG - Automated Ultrasonic Inspection Technique Development for Steam Generator Tube

As a part of the steam generator tube inspection system development, the ultrasonic investigation has focussed on developing a rapid inspection technique, and a number of UT inspection heads have been investigated. A prototype 16 element head conceived by OHRD was built and tested. The test results showed the probe failed to provide consistent performance. The overall inspection head (less than 10 mm in diameter) and the elements (about 2 mm in diameter) are so small that repairs are virtually impossible. Later, a commercial 16 element head became available, and preliminary tests showed that the sensitivity of this probe was acceptable. Further development of a multi-element probe for this inspection will continue.

A rotary NUCON probe has been purchased and it is currently being tested. The rotating feature of the NUCON probe would permit a full volumetric inspection, but it is expected that any inspection with the probe would take much longer than the multi-element approach. This NUCON probe will also be used for investigating the possibility of broach plate deposit inspection.

Although multi-element inspection heads for steam generator tube inspection currently exist, all have a problem with limited ultrasonic coverage of the tube. Therefore, in addition to the rotating NUCON probe, the development of a multi-element head that uses curved, line focussed probes constructed from a copolymer material is being investigated. There are a large number of technical problems associated with the construction of such an inspection head, but steady progress is being made. It is hoped that such a head may provide close to 100 percent coverage of the tube being inspected.

Preliminary test of the inspection prototype showed that it will be required to be modified to suit field application. The software being developed is applicable to both steam generator tube inspection and sludge pile characterization. To extend the single channel capabilities of the current system, a system that can deal with sixteen channels operating simultaneously is also being developed.

The current prototype is capable of performing inspection for the area immediately above the tube sheet and the sludge pile. The axial scanning length of the probe will be modified in the future to perform a full length tube inspection. Studies on sludge pile detection and wall thickness measurement will continue.

STEM Development

The Bruce STEM (Scanning Tool for Elongation Measurement) system was developed in 1978. Due to the lack of automatic recording devices in the remote consoles of both the Bruce A and B systems, the measurements required a lot of manual recording as well as post test data retyping which could lead to longer measurement times and unnecessary errors.

A computer system, which has been integrated to the existing remote console, allows the P/T elongation measurement to be faster and provides more accurate data recording. In early 1989, the computer system was demonstrated to Bruce A and B operations in a mock-up condition. During November 1989, the computer system was successfully implemented in the Bruce B Unit 6 STEM measurement.

A portable COMPAQ computer has been purchased for the Bruce A and B STEM system. The same computer will be also used for Darlington STEM measurements. A new operating software program for providing graphic and data presentation on-line is currently being developed for the computer system. This program will provide the operator information about the quality and quantity of the data being measured.

Calandria Vault Ring Thermal Shield Support Bracket Wall Thickness Measurement

Following a request from CPSD, various techniques were investigated for remotely measuring the thickness of these corroded brackets. Due to the surface condition (predicted) of the brackets, conventional immersion ultrasonics was discarded in favour of a near-commercial EMAT (ElectroMagnetic Acoustic Transducer) device specifically developed for measuring the wall thickness of corroded boiler tubes.

A pre-production device, which was rented from the U.K., has been tested on corroded plates of suitable composition. In a laboratory condition, the device works well on plate with adherent scale, but not at all on flaky or polished plate. Due to the unknown surface condition of the brackets, a special caliper is also being developed in parallel for this measurement to provide additional data which can be used to verify the result from EMAT measurement. This mechanical caliper consits of a LVDT and an electrical conductivity measurement device. The LVDT will provide thick

ness reading of the brackets and the conductivity device will check any oxide at the area being measured by the caliper.

Both the EMAT and the caliper will be attached to the B&W made delivery mechanism named ANDREA. Two special mounting fixtures were built to allow the EMAT and the caliper to be attached to the gripper of the ANDREA arm. These devices have been tested in the mock-up at AECL SPEL.

A Special Probe Pan for Pickering Low Pressure (LP) Turbine Disc Inspection

Both Pickering and Bruce Nuclear Generating Station LP turbine rotor discs can be susceptible to stress corrosion cracking in the bore and keyways. Automated ultrasonic inspection systems have been developed by Central Production Services Division (CPSD) to perform periodic inspection to ensure the structural integrity of the discs.

In early 1989, CPSD requested that a special ultrasonic probe pan or probe manipulator be developed and integrated to the existing LP turbine inspection equipment "BONNIE" system for the inspection of Pickering rotors (NEI-Parsons design).

Two special probe pans have been built to accommodate inspection of NEI-Parsons rotors and they are suitable for use on General Electric rotors as well. Limited access between the turbine discs (approx. 30 mm groove) was the main difficulty encountered in the design of the device. The main function is to access the sloped web face of the discs and to provide a proper probe-web surface contact.

The probe pans are remotely and individually manipulated while the BONNIE manipulator controlled by the central computer station performs scanning in a desired direction. Both laboratory tests and site inspection showed that the device met the design requirements for the LP turbine ultrasonic inspection.

Development of a Slope Detector for P/T Sag Measurement

The purpose of this project is to investigate the feasibility of developing a sag measuring device applicable to in-situ inspection of fuel channels. The device will have a targetted radiation tolerance of at least 200 Mrads, almost four times that of the current sag transducer used in CIGAR.

Various techniques, such as an electrical resolver with a mass pendulum, eddy current technology, and a strain gauge measurement device, are currently being investigated for slope measurement. There are a large number of technical problems associated with the construction of such a sag measurement device, but steady progress is being made.

CIGAR - Ultrasonic Flaw Sizing Using Pitch-Catch

A report was issued outlining the theoretical analysis of pitch-catch (transmit-receive) ultrasonic methods of flaw sizing in pressure tubes. Experimental results based on a limited number of artificial defects (notches) showed good agreement with the theoretical results. Since then, a wide range of additional artificial defects encompassing various shapes, depths, orientations (axial and circumferential) and location (inside and outside surfaces) have been fabricated and pitch-catch responses are being collected and evaluated. A report summarizing the results is being prepared. This work has been applied, using the research developed by GDCPS (Generalized Data Collection and Processing System).

CIGAR - Uncracked Blister Detection Modules

The fast scan blister detection system developed for SLAR and adapted for use on CIGAR (SEE SLAR - Ultrasonic Blister Detection System) can only detect blisters that contain cracks. Research work has shown that uncracked blisters can be detected by inspecting the tube with a single skip, high refracted angle shearwave pitch catch probe pair. The method depends on the lower shearwave velocity in the blister hydride than in the bulk material. Blister detection is characterized by a significant amplitude reduction caused either by interference or refractive dispersion of the beam, and by an increase in the time of flight due to the lower velocity in the blister material.

CIGAR inspection head modules containing both circumferential and axial probe pairs for uncracked blister detection have been designed and will be fabricated in early 1990.

CIGAR - Ultrasonic Flaw Detection Calibration Upgrades

At present, CIGAR ultrasonic flaw detection calibration is performed outside the reactor using calibration tubes containing standard notches. Relative system sensitivity between calibration and in reactor inspection is determined by performing pitch-catch "power checks" both in the calibration standard and in the tube to be inspected. An alternate calibration system using an undersized zirconium calibration ring was proposed. After delays in obtaining suitable prototype calibration rings and notches, the studies have been completed. Good correlation between notch sensitivity in full size and undersized rings was established and implementation of the new calibration method is underway.

CIGAR - Ultrasonic RPP Cable Reflections

The CIGAR ultrasonic inspection systems use Remote Pulser Preamplifiers (RPPs) to mitigate the effects of long cables between inspection instruments and transducers. A problem that occurs with long cables, that act as transmission lines for the high frequency signals, is ghosting; lower amplitude copies of the transient signals superimposed on the original with a time shift. This is caused by reflection of the signal in the cable if there is an impedance mismatch between the cable and the receiving instrument. This same problem was noted when the RPPs were in use despite measures taken by the manufacturer to match the instruments to the line. Time Delay Reflectometry studies and other research led to a clearer understanding of the problem and a solution has now been found to eliminate this undesirable effect.

SLAR - Umbilical Cable Tests

Specimens of SLAR umbilical cable that had been irradiated and mechanically cycled were found to have significantly changed electrical properties. For the co-axial cables used for SLAR ultrasonic testing, the measurements showed an increase in capacitance and a decrease in core insulation resistance.

OHRD performed Time Delay Reflectometry (TDR) and functional tests and showed that, while real, the changes did not significantly influence the inspection systems response. It was concluded that the existing cable specification is acceptable for manufacturing use (ie, monitoring manufacturing process parameters) but it is unnecessarily severe for determining end of life during cable endurance tests.

SLAR - Ultrasonic Blister Detection System

CIGAR inspection head modules that hold an array of SLAR ultrasonic blister detection probes were fabricated and used by CPS personnel to inspect selected channels in Bruce Unit 2. Some of the channels found to have misplaced spacers and contact were SLARed using SLARette (SLAR using a modified CIGARette drive).

Assistance was provided to Design and Development in preparing submissions to the AECB for approval to use the SLAR system. Also, a study of the relative capabilities of the SLAR and CIGAR systems for detecting and characterizing blisters is underway.

SLAR - Upgrade of Wall Thickness Measurement System

The SLAR wall thickness measurement system provides information used to correct Eddy Current measurements of pressure tube/calandria tube gap. It was designed in the mid 1980's to meet the original design requirement of the SLAR system. As the SLAR system matured into the testing phase, deficiencies were noted in various systems.

The wall thickness measurement system was changed from a single ultrasonic instrument with multiplexed transducers to a duel instrument system with multiplexing of pairs of probes. The changes were completed in early 1989 and have proved to be very successful.

SLAR - Electrical Filters to Reduce Inspection System Interference

During commissioning of the SLAR system, transient electrical interference generated by Bruce fuelling machine drives and detected by ultrasonic inspection systems caused difficulties. With the assistance of OHRD Electrical Research personnel, filters were designed to reduce the high frequency content of the fuelling machine's pulse width modulated chopped DC drives. Similar filters are now being investigated for use on the CIGAR system which has similar, though less powerful, drives.

Calandria Tube - Horizontal Flux Detector Tube Clearance

A problem by NB-RPC to develop a tool for measuring the clearance between horizontal flux detector tubes and calandria tubes was monitored for COG. The tool used ultrasonic methods similar to those proposed by Dolbey of OHRD in 1979. Advice on the design and suitable components for use in a radiation environment were provided. The tool was developed in three months and successfully used on a Pt. LePreau flux detetor in April 1989. A proposal has been submitted to develop a more advanced tool that can also measure the slope of the flux detector tube. Development of a version of the tool for deployment in poison injection nozzles is also proposed.

Real Time Radiography (RTR) for CPS and OHR Applications

Following a meeting with senior RT technicians from Pickering, Bruce, Darlington and Lakeview stations, it was agreed to continue evaluation of RTR systems for power station RT inspections. This meeting establishes a link with CPS station RT requirements including any upgrades to RT equipment and methods.

Initial steps included a demonstration with a 3M R&D engineer at Darlington NGS site. The 3M paper may replace RT film for the valve closure application. Evaluation of RTR systems will follow this step starting with sending an application sample to suppliers, in order to confirm the 2-2T RT image sensitivity required by ASME.

SLAP (Spacer Location at Power, COG (#6556)

The objective of this project is to develop an eddy current garter spring detection probe with performance similar to the current CIGAR system but suitable for use while the reactor is at power. A prototype probe manufactured with an alumina coil form, ceramic coated magnet wire and entirely encased in a thin shim of titanium has been completed this year. The unit has been subjected to maximum reactor pressure and temperature conditions and survived with no perceptible leaks. Currently, the unit is awaiting an explosively welded transition ring which will be used to join an Inconel clad cable to the titanium clad probe. A radiation testing plan has been submitted to CRNL for review and approval.

CIGAR Gap Measurement

The EC gap probe used for pressure tube to calandria tube gap measurement must be compensated for its response to pressure tube thickness variations. This year an investigation into the way the EC probe senses thickness variations was completed. The probe is modelled as a separable 2D linear filter which produces a smoothed output from thickness values over a region approximately 100 mm axially and 360° rotationally. The shape of the probe's influence function is determined from its response to a machined thickness using a deconvolution algorithm originally developed for a spectroscopy application. The influence function is described by parametrized functions suggested by the electromagnetic interaction between the probe and pressure tube and then fitted to the experimental results. The final model is easily applied to the UT data and successfully predicts the EC thickness response. This new compensation method is now being coded into the CIGAR system by CPS and an external software consulting group. A paper describing this work was prepared for the Fuel Channel Technology Seminar (November 1989, Allison).

Annulus Gas Flow Measurement System

A non-contact, non-intrusive flow measurement system has been developed for annulus gas system tubing (pigtails). The method employes a carbon dioxide infrared laser to heat a spot on the tube, and an infrared camera to monitor the change in the heat distribution as a result of flow. Data acquisition is facilitated by a video digitizer which allows computer processing of the image data. A normal video camera and a visible helium-neon laser, as well as the appropriate motion control equipment is used to aim the system at the correct tube by remote control. Two complete measurement systems have been built and tested for use at site. One of them has already been used at Pickering unit 3. Uncertainties in the data obtained indicate that further work is needed. This project was a joint effort between the ND&FE Section, Materials Chemistry Section, Science Section, Applied Mechanics Section (Research Division), the Inspection and Maintenance Department (CPS Division) and the Nuclear Systems Department (Design & Development Division).

Pressure Tube Inspection Systems (SPIDER)

The feasibility of a pressure tube inspection system with self contained mechanical drives for providing rotary and axial motion has been examined. An initial conceptual design indicates that an axial drive with six 38 mm (1.5") driven wheels which extend and retract to accommodate pressure tube diameters from 95.25 mm (3.75") to 114.3 mm (4.5"), could be designed to fit into a 305 mm (12") length.

A special helical cable has been designed to support the SPIDER (Self Propelled Inspection Device for Evaluating Reactors) pressure tube inspection concept. This design incorporates twelve 50 ohm coaxes and 22 solid conductors. The helix outer diameter is less than 96 mm (3.75") and the compressed length is about 203 mm (8"). The extended length is about 6.6 m (21' 8") which

should enable it to cover the full length of a pressure tube. A cable manufacturer has made an attempt to manufacture this cable with partial success. He has succeeded in producing a helical cable with a compressed length of 100 mm (4") which stretches out to 3.3 m (11') or half the length of a pressure tube. It has 12 coaxes and 20 usable solid conductors.

1.3 Pressure Tubes

EC H_2/D_2 Concentration Measurements (COG #3550)

The objective of this project is to develop a non-contact Eddy Current (EC) technique to accurately monitor the change in pressure tube resistivity over a range of 20°C to 400°C. An estimate of the H_2/D_2 concentration may be made from the resistivity vs. temperature plot using methods developed by K. Tashiro (Materials Integrity Section COG #3550).

This year the EC resistivity probe underwent a significant mechanical redesign. This was necessary to overcome problems in waterproofing the probe and its insulation and to minimize movement of the probe during heating and cooling. The new design consists of probe coils wound on a thin high strength alumina tube suspended on high temprature O rings. Coolant flow through this tube as well as ceramic insulation over the coils should keep the probe at a relatively constant temperature while the pressure tube is heated. This is necessary to reduce undesirable influences on the output signal and allow it to be considered to be a function of pressure tube resistivity only. Performance data will be available as soon as a resistance heating system is fitted to the experiment mockup.

Post Removal Ultrasonic Inspection of PT P4-L20

In February 1989, CIGAR inspection of top of ingot tube P4-L20 revealed a 300 mm long flaw in the back end of the tube. Subsequently, metallography confirmed the presence of a manufacturing flaw in the offcut. This flaw in the offcut was not detectable by any of the nondestructive inspection methods tried; ie, conventional ultrasonics, high frequency or eddy current methods. The flaw was detected in reactor because it had opened up in service and oxide forming in the crack had distorted the inside surface of the tube. The severity of the flaw was difficult to assess from the CIGAR inspection results. After the tube was replaced, the flawed section was placed in the bays at AECL-CRNL and re-inspected using the research GDCPS system. This work confirmed that tight, oxide filled flaws are relatively transparent to ultrasound but that time of flight normal beam and shearwave pitch catch methods could provide useful sizing information in many instances.

Post Removal Ultrasonic Inspection of Delayed Hydride Cracks

CIGAR inspection has detected delayed hydride cracks (DHCs) in the rolled joint region of a few tubes in older reactors. Generally, the amplitude of response from these flaws has been smaller than expected. To better quantify the relationship between response amplitude and size, ultrasonic measurements were made of a number of DHCs in tubes removed from Pickering Unit 4 in the mid 1970s. Subsequently, the DHCs were examined metallographically to determine the true size and nature. Preliminary results confirm that tight oxide filled flaws such as DHCs are less reflective than equivalent sized open notches. Modified inspection methods are being investigated to see if detection can be improved.

Bruce Unit 3 Pressure Tube Leak Search

In late September, 1989, increased annulus case moisture collection indicated the presence of a very small pressure tube leak. Subdivision of the annulus gas system showed that the leak was confined to one string consisting of twelve fuel channels in column 11. A CIGAR inspection of all twelve pressure tubes was performed. In addition, Research Division used the GDCPS in conjunction with CIGAR to determine the tightness of rolling in the rolled joints and to determine whether there was water in the joint rolling grooves. Water was detected in some grooves of a number of west face joints. One joint, U11 west, had water in all three. Also, the CIGAR flaw detection system located an outside surface scratch that passed through the rolled portion of this joint. No other possible leak paths were detected in the 12 channels. B3-U11 was replaced and the leak was not present after the unit returned to power.

Pickering Unit 6 - CIGAR Evaluation of Pressure Tube Debris Damage

CIGAR inspection of Pickering Unit 6 pressure tubes during September 1989 revealed debris damage in a number of them. The Research GDCPS system was linked to CIGAR and used to collect time of flight ultrasonic data for improved characterization and sizing of those flaws that were dispositionable. Normal beam and pitch catch shearwave B-scans provided the best information for flaw interpretation. The depths and shape of these flaws were determined without the need for draining the channels to perform dry channel eddy current and CCTV visual inspection. This avoided lengthening the outage.

Bruce Unit 6 - CIGAR Evaluation of Pressure Tube Debris Damage

After successful use of the GDCPS system with CIGAR for debris damage assessment in Pickering Unit 6, it was called on again when dispositionable ultrasonic flaw responses were found in a number of Bruce Unit 6 tubes. The size and depth of a number of flaws caused by debris and two fret marks from unsupported inlet bundle wear pads were evaluated. Again, normal beam and pitch catch shearwave B-scans were found to be the most informative techniques for these evaluations.

Pressure Tube Manufacturing Inspection

New pressure tubes are subjected to ultrasonic and eddy current flaw detection inspections during their production. The tubes were formerly manufactured by one company and inspected by a different company. Prior to the order for replacement tubes for Pickering Units 3 and 4, the system was changed and the tubes are now inspected by the tube manufacturer. Assistance has been provided to AECL-SPEL, who procure the tubes for Ontario Hydro, and to the tube manufacturer to set up the equipment and procedures required to perform the ultrasonic inspections to meet the manufacturing specification. In particular, recently installed equipment for performing high frequency ultrasonic inspection is being monitored and upgrades have been proposed to overcome occasional difficulties.

NDE of Tunnelling DHCs in Pressure Tubes

The phenomenon of DHC tunnelling in pressure tubes (the enlargement of a crack within the wall without breaking through the inside or outside surfaces) has been observed in Bruce Unit 2 and is being studied by the Research Materials Integrity Section. A laboratory grown tunnel DHC was inspected using CIGAR ultrasonic pitch-catch shearwave methods and an image of the crack cross-sectional shape was produced. Metallography on the specimen showed excellent agreement be

tween the image and the crack. This technique will be used for monitoring the progress of crack growth during future experiments.

Pressure Tube Contact Detection System

A method for measuring pressure tube to calandria tube contact areas has been investigated. This concept uses a standard ultrasonic probe focussed on the outer surface of the pressure tube, and a low frequency vibration source to cycle the contact forces. Since the reflected signal amplitude varies with contact force, the amplitude of the reflected signal is modulated at the frequency of the vibration source. It is hoped that relatively simple signal processing will enable the detection of this modulation. If that is the case, then it is anticipated that this technique will also allow the detection of garter springs with open circuit girdle wires.

Uncracked Blister Detection Module

The initial version of this module used very high angle (approx 70 degrees) shear waves in pitch-catch to detect amplitude increases in the presence of blisters. While this module could detect blisters, it tended to be very sensitive to small offsets in position.

A second module was built using approximately 55° shear waves in pitch-catch. This second module works on the loss of signal occurring when a blister is traversed, and is similar in application to CIGAR pitch-catch. In the laboratory, the module could clearly detect blisters of 3mm diameter, 0.5 mm depth, and appeared little affected by the presence of cracks in the blisters. Also, the module still performed well when significantly offset, indicating great robustness.

While initial theories indicated that the slightly lower shear wave velocity in the blisters was causing refraction, subsequent evidence suggests that the amplitude changes were being caused by destructive interference due to the small velocity changes. Later tests showed this destructive interference could be obtained with a variety of angles and transducers, provided they produced a flat wavefront.

Due to the great demand and ease of implementation of this module/technique, CPS will fund the final research and production of modules for the Pickering 4 inspection in the Spring. However, the optimum module arrangement has not been finalized.

Overall, this uncracked blister detection module has been a very successful development.

Blister Crack Depth Measurements

Most emphasis was placed on finalizing the parameters for measuring blister crack depths, and on making a reactor-ready system. Some time has been spent on investigating DHC-type cracks.

Early in the year, considerable emphasis was put on converting the laboratory, free-transducer, technology to a fixed-transducer, CIGAR-type scanning technology. A CIGAR-compatible module with 45-45° and 55-55° axial-circumferential pairs was manufactured. This module was tested on a series of laboratory (air-jet grown) blisters supplied by the Materials Integrity Section.

Due to the low signal amplitudes from the crack-tip diffracted signals, extensive signal processing was required to detect and optimize the signal amplitudes. A PC-based pulser was used, which permitted extensive signal averaging to reduce random noise. Both high pass and low pass filtering were used. SAFT (Synthetic Aperture Focussing Technique) was used to focus the resultant B-scan, and to further improve signal-to-noise ratio.

The results on the cracked blisters showed that the 55-55° axial probe combination produced the highest diffracted signal amplitudes. This was also observed on the previous laboratory tests. However, extensive signal averaging and SAFT were required to detect some of the signals. Actual blister crack depth measurements were made from the parent tube backwall, using a further process called the magnitude of the analytic signal.

Two blisters in particular were examined in detail, and subsequently metallographically sectioned and polished. The results showed that the ultrasonic measurements were well within the specified $\pm$ 0.1 mm, and in most cases were within $\pm$ 0.05 mm. (Even though only two blisters were used, there are two different angles, two different directions and several possible analysis techniques). A demonstration on measuring blister crack depths was given to selected CPS personnel in May.

The actual in-service implementation of the module was shifted down the priority list since structural integrity factors were indicating that any blistered tube (cracked or not) would be removed. An uncracked blister module is in preparation (see COG WPIR #6578). The software modifications required for the in-service implementation should be ready for the Pickering 4 shutdown in the Spring of 1990. Due to the complexity of the inspection process, it is anticipated that the operators will simply collect the raw ultrasonic data, and transfer this to OHRD for analysis.

For DHC depth measurements, a CIGAR-compatible, variable angle transducer holder has been developed. This will be used with similar software to that developed previously to develop time-of-flight techniques for DHC depth measurements. Previous work (1988) indicates that only time-of-flight approaches offer the potential accuracies required ($\pm$ 0.1 mm).

Some work was performed on analysing an ID manufacturing defect detected in Darlington 1 R07. This defect was detectable by conventional CIGAR-type ultrasonics. The defect's depth was readily measured from the OD using the high frequency (100 MHz) transducers used in the manufacturing inspection.

Determine Hydride Platelet Concentration by Ultrasonics

Progress has taken place in four areas: scanning acoustic microscopy, shear wave birefringence, differential velocity measurements (DVM), and nonlinear ultrasonics. Acoustic microscopy and shear wave birefringence have proved unusable, DVM has had two downs but now looks encouraging, while nonlinear ultrasonics is showing great promise.

Acoustic Microscopy Both Harwell/Oxford University and Sherbrooke University have determined that radially-oriented platelets are only detectable under very specific surface conditions. Specifically, the surface should be smooth and platelets should be more or less visible optically. Contrary to initial opinions, this suggested that the acoustic microscope is actually seeing surface effects, not a complex velocity interaction. This suggests that through-the-oxide imaging will not be feasible, so acoustic microscopy will have only very limited applications. While the results have not been finally documented, they will recommend that no further work be done with this technique.

Shear Wave Birefringence Queen's University have performed more work using normal beam shear wave birefringence on partly hydrided plates. This technique is the same as that successfully used to detect uncracked blisters. (The current work was not financially supported by COG, though OHRD supplied the specimens.) The shear wave birefringence technique did not appear capable of detecting the hydrides. The time changes due to hydrides should be of the order of one nanosecond, which is extremely small. Other effects, such as the presence of oxides or surface

residual stresses, appeared to swamp any changes due to the presence of hydrides. Once documented, no further work will be performed in this area either.

Differential Velocity Measurements This technique is very similar to the shear wave birefringence, but uses different generation modes and metal paths. DVM sends waves circumferentially round the tube, giving 360 mm of path as opposed to 8.4 mm. Axially and radially polarized shear waves are generated by EMAT devices, and their arrival times compared in hydrided and unhydrided tubes. The first result (in 1988) showed approx 60 ppm hydride gave about 60 nanoseconds time difference. Follow-up tests in 1989 showed that the first set of specimens was too short, and end effects destroyed the timing. The second tube was long with various hydride levels in it. However, this tube had a relatively rough, ground surface, which destroyed the timing of the waves.

The third tube (approx 131 ppm H) showed encouraging results, with 120 nanoseconds time difference between the hydrided and unhydrided areas. This is in good agreement with the first result, though the overall timeshifts are small. This tube had an as-received microstructure, and the tube has been "aged" (500°C for 6 hours) to give a pseudo-reactor type microstructure. The tube will be retested using DVM.

NonLinear Ultrasonics During the summer, Sherbrooke University discovered that stressing hydrided and unhydrided specimens altered their velocities in different and unpredictable ways (nonlinear ultrasonics). Since these stressing results were difficult to reproduce, Sherbrooke switched to sending interacting ultrasonic waves (a similar effect) and observing the harmonic waves generated. Using a mix of 30 and 150 MHz input waves, the amplitude of a harmonic wave showed a distinct correlation with hydride concentration. This was a most encouraging result, as it showed a potentially useful technique, and the results were reproducible.

Sherbrooke then performed similar tests on a more carefully prepared set of specimens, ranging from as-received to 120 ppm. A duplicate set were also "reactor-aged" (6 hours at 500 C) and also tested using harmonic generation. Both the as-received set and the reactor-aged set showed similar harmonic wave generation characteristics, though the slopes of the two curves differed. (Subsequent preliminary metallography has shown higher concentrations of beta-Nb in the reactor-aged material.) The future direction of harmonic wave generation is not clear, though there are a number of questions to be answered. We do not appear ready to build a reactor-ready system yet.

Magnasonics have also performed pressure/velocity tests on their hydrided tube (ie. nonlinear ultrasonics). The results show nonlinear behaviour, similar to Sherbrooke's pressure/velocity results, which is encouraging for two reasons. First, it supports the hypothesis that nonlinear behaviour is a general phenomenon in these tubes, as Magnasonics used different wave modes and wave directions. Second, it offers a potential practical method of performing measurements in reactor.

Queen's are performing some pressure/stress/temperature tests on hydrided disks supplied by CRNL/OHRD. No results are available yet.

OHRD Research Recently, OHRD hired a specialist in nonlinear ultrasonics, who has started to pull all the above external work home. Work at OHRD on bulk hydride concentration measurements is being pursued along two avenues: linear and nonlinear acoustic effects.

A fair amount of work has been done externally using standard linear techniques. These include velocity, attenuation, and spectral measurements. Recently, OHRD has measured both shear and longitudinal wave velocities along all the principle axes in Zr-2.5%Nb pressure tubes. The velocities in Zr-1.7%H were also measured. Using these values, a theoretical model of Zr-Nb with Zr-

1.7H platelets was made. The model predicted that the shear wave velocity of the hydrided material would decrease while the longitudinal wave velocity would also increase. These changes were small, however, perhaps in the order of 10^{-5}.

Based on these results, it was concluded that the work Magnasonics had done on measuring velocity differences of SH and SV Lame waves was perhaps the most feasible technique to measure hydride concentration so far. This conclusion is based not only on the advantages previously mentioned (long metal path and insensitivity to geometry), but also because (as can be shown theoretically) the DVM technique makes use of the fact that the shear wave velocity decreases and longitudinal wave velocity increases with concentration.

Tests have also shown that hydrided and unhydrided material have a 50% difference in acoustic impedance for shear waves. However, because the platelets are so thin, calculations show that very little energy will be reflected by them, except at high frequencies. For example, 0.6% will be reflected at 10 MHz, 4% at 100 MHz. Although various acoustic microscopy techniques have already been studied with little success, perhaps a high frequency method more sensitive to shear waves may be more useful.

Experiments to measure nonlinear parameters of hydrided pressure tubes are being prepared or performed at OHRD. Measurement of velocity as a function of temperature is well underway, however no conclusive results are yet available. Preparation for measurement of velocity as a function of pressure and propagation of high amplitude ultrasonic waves is also in progress.

1.4 1990 Work Plan

As with previous years, the 1990 NDE work program will cover many areas, with the emphasis on pressure tubes. For eddy current, it is expected that the SLAP and GAP programs will be finalized, and applications of multifrequency eddy current will be investigated. For ultrasonic digital signal processing, major emphasis will be placed on finalizing the detection of tight garter springs, including transducer modifications, as well as further work on deconvolution and visualization of ultrasonic signals and scans. The uncracked blister detection module will be finalized for the Pickering 4 shutdown, the manufacturing inspection will be upgraded and the BLIP B-scan encoder will be installed. Considerable effort will continue to be placed on developing nondestructive methods of measuring hydride concentrations in pressure tubes, either by ultrasonics or by the resistivity method. Other ultrasonic techniques will be investigated for detection of tight garter springs and PT/CT contact. Ultrasonic crack-tip diffraction will be finalized for blisters and initiated on inside surface defects. High frequency transducers will be made for improved pressure tube inspections, and the EMAT device for on-power inspection of pressure tubes improved. From an electromechanical design viewpoint, work will continue to emphasize the NPLA of Pickering A. Bruce STEM modifications, the BHWP scanner, plus new sag devices and a profilometer for CIGAR will be undertaken in 1990, plus work on a spacewalker and on SPIDER for pressure tube inspections. A technique for the non-invasive moisture detection in pigtails will be pursued. From a software perspective, much of the time will be spent on introducing the Windows environment for scanning, plus BLIP, BHWP scanner, spacewalker and CIGAR support.

2.0 FRACTURE MECHANICS RESEARCH AND APPLICATION

2.1 Darlington Leak-Before-Break Program

Darlington LBB - Analysis of Reactor Headers

Except for production of the final reports, this joint project (with the Stress Analysis and Computer Applications Unit, Mechanical and Equipment Engineering Dept) is nearly complete. Finite element analyses to determine the J-integral ("J") and tearing modulus ("T") for several crack sizes in the reactor inlet and outlet headers were repeated several times to account for newly measured tensile properties and as-built header dimensions.

Initial (elastic) analyses were performed to determine crack opening areas for a series of six crack lengths for each header. These were subsquently used to estimate leak rates. It was found that numerical results for leak rates could be adequately curved fitted as a cubic polynomial versus crack length. These curve fits were then used to obtain crack sizes corresponding to a detectible leak rate. The same finite element models were used to obtain stress distributions in uncracked headers for use in fatigue crack growth simulations.

Having determined the crack size corresponding to a detectible leak (the "refrence crack length", RCL), models were constructed for both headers with crack sizes of both one times and two times the RCL. Additional models with crack sizes of about 5% larger were constructed to determine the tearing modulus.

Since the CPU time required to effect the elastic-plastic analyses of all cases on available mini-computers was estimated to be in the order of months, the final cases were of necessity run on an IBM 3090 mainframe having vector capability. The mesh generation effort was itself very time consuming; a number of features addressed specifically to these components were included in an in-house mesh generation program to reduce this effort.

To reduce the numerical data into a form for comparison with measured J-T resistance curves, it was found that, for a given crack length, the J-integral could be fitted quite well as a function of pressure, P in the form

$$J = A \cdot P^2 + B \cdot P^{n+1}$$

where "n" is the Ramberg-Osgood hardening exponent (ie. in a similar form as the EPRI estimation scheme, even though the header and crack geometries are more complex). By obtaining the curve fitting constants (A and B) for two slightly different crack lengths, then differencing the fits, the tearing modulus was obtained as a function of pressure. The intersection of the applied and material J-T curves was then obtained numerically by Newton-Raphson iteration.

A review of the assessment procedure was presented at the recent OECD Specialists Meeting on Leak-Before-Break in Water Reactor Piping and Vessels.

Darlington LBB, J-Resistance Curves; Additional Tests

Leak before break assessments of Darlington NGS primary heat transport piping have indicated that the critical components within the scope of the program are the 22" steam generator inlet piping elbows and 21" NPS Sch 100 heat transport pump discharge piping. Twelve additional J-resistance curve tests were conducted on the 22" diameter elbow and the 21" NPS Sch 100 pipe material. The test procedure was identical to that used in a previously reported Darlington J-resistance

curve material test program. The 22" pipe elbow was significantly tougher than the 21", 22" and 24" NPS Sch 100 pipes, possibly due to its higher ductility. The fracture toughness of the 21" pipe was comparable to the fracture toughness values obtained previously from testing 12", 22" and 24" NPS Sch 100 pipes.

Development of Fatigue Crack Growth Computer Program

Predictions are made of the fatigue crack growth of postulated part through-the-wall cracks in the primary heat transport piping as a part of the "defense-in-depth" strategy of the Darlington LBB program. This involved the development of a computer program to perform the calculations for an entire piping system. Modifications were made to this computer program in 1989 to increase the flexibility and scope of the calculations. A draft report detailing the technical changes, a draft validation report, and a draft user's manual were written and submitted to the Mechanical Equipment Department for comments.

2.2 Pressure Tubes

Fatigue Crack Growth of Zr-Nb Pressure Tube Material

The objective of this COG program, which is jointly being carried out at Ontario Hydro and CRNL, is to assess the fatigue crack growth rate behaviour of Zr-2.5Nb pressure tube material in a simulated CANDU PHTS environment. Work at Ontario Hydro will concentrate on evaluating environmental effects, such as high dissolved oxygen concentrations, while work at CRNL will address effects of irradiation on the fatigue crack growth rate.

Work was concentrated on commissioning the autoclave fatigue testing facility. Numerous problems were resolved by small design changes and operational modifications, and, following two trial fatigue tests, the facility became fully operational in December 1989.

The first fatigue test was carried out under conditions approaching normal CANDU operating conditions. The test was conducted at 290°C and 8.4 MPa so as to minimize the rate of leakage from a static seal in the autoclave. Water chemistry was maintained at a pH of 10.5 and a low dissolved oxygen concentration of less than 20 ppb. The specimen, containing approximately 40 ppm of hydrogen, was loaded using a constant load amplitude sinusoidal waveform having a R-ratio and frequency of 0.2 and 0.4 Hz, respectively.

Preliminary results of the test, when compared with previously obtained data for the same material in air at 300°C, showed little or no enhancement in fatigue crack growth rate. These results were expected because the relatively high loading frequency can reduce the contribution of a corrosion-assisted mechanism in the fatigue crack growth process. Future tests will use a lower loading frequency to assess the corrosion fatigue effect.

Pressure Tube Fitness for Service

Detailed evaluation procedures for the assessment of sharp and blunt flaw indications in a Zr-Nb pressure tube have been further developed. The procedures include crack driving force calculation procedures, notch-tip stress calculation procedures, sub-critical crack growth calculation procedures, and material properties. The evaluation procedures are being developed as a part of the "Fitness-for-Service" Guidelines, jointly by Ontario Hydro and AECL. A draft report containing the detailed evaluation procedures has been sent out for comment. Difficulties have been countered in developing acceptance criteria which ensure the structural integrity of pressure tubes and are not overly conservative.

Calculation of Critical Crack Length in Zr-Nb Pressure Tubes

A COG-funded project to improve the accuracy of the calculation of the critical length of a through-the-wall crack in a Zr-Nb pressure tube from small specimen material test results is underway. Progress to date includes a literature survey to assess the various fracture mechanics methodologies which may be applicable. As well, three-dimensional finite element calculations have been carried out to determine the crack-driving force J-integral for one crack length and a range of material stress-strain curves. Comparisons were made with an approximate analytical formulae which is currently being used to calculate the critical crack length. The effects of pressure tube end loading and pressure acting on the crack faces were also assessed. Three-dimensional elastic finite element calculations to determine the J-integral for the curved compact tension specimen (used for determining J-R curves for Zr-Nb pressure tubes) were also carried out.

Evaluation of Postulated Flaws Under SLAR Stresses

The Spacer Location and Repositioning (SLAR) operation induces stresses in the Zr-Nb pressure tube which are well above normal operating stresses. The effect of SLAR stresses on flaws, including cracked blisters, which may exist in the pressure tube was assessed. The fatigue behaviour and safety margins against fracture were calculated. This information was used by CPS in assessing the impact of SLAR on flawed pressure tubes, as well as input into determining the inspection requirements of SLAR.

Evaluation of Fret Marks in Bruce Unit 2

Blunt flaws have been detected in pressure tubes in Bruce NGS Unit 2. The flaws have been characterized as fret marks. An evaluation of the flaws was performed based on criteria to prevent crack initiation due to fatigue and delayed hydride cracking (DHC). The evaluation results indicated that the flaws may be susceptible to DHC for normal operating conditions or thermal transients. A more refined analysis is underway.

Stress Relaxation at Notches Due to Creep

The preliminary investigation of stress relaxation at notches due to creep has been finished. This study was carried out with the cooperation of David Badie of the Materials Integrity group. Numerican simulations were made using the finite element code ABAQUS. The creep model in CRNL-4000 with modifications was used. Isotropic material properties, both visco-elastic and visco-plastic stress strain behaviour, were assumed for simplicity. Because the fret marks found in Bruce NGS, Unit 2 were located near the rolled joint region where irradiation damage is relatively small, irradiation creep and growth were ignored. A transient term by Ibraham of CRNL was used to account for the primary creep effect. The numerical simulations produced mixed results. The stress at the notch root decreases significantly in a relatively short time. However, once the effect of the transient term diminishes with time, stress at the notch root begins to rise. Simulations were also run without the transient term but including irradiation creep. The result of the visco-elastic run showed that the stress at the notch root decreases slowly but continuously with time. However, the simulations with visco-plastic material properties showed that the stress at the notch root increases initially until it converges with the visco-elastic solution. The visco-plastic solution converges with the visco-elastic solution earlier when the amount of plasticity at the notch root is small.

Based on the results, the creep model used was found to be inadequate. Furthermore, ABAQUS was found to be very difficult and awkward to use for creep simulation. Therefore, it is recommended that a more fundamental investigation into stress relaxation at notches due to creep should

be carried out. A better creep model should be implemented. For numerical simulation, a code which allows more control over solution convergence should be used.

Fret Mark Analysis for Pickering NGS Unit 5

As requested by CPS, the fret marks found in Pickering NGS Unit 5, fuel channels J11, L18 and N09 were analysed. The elastic stress concentration factors for these fret marks were determined by finite element analysis. Because the fret mark in N09 was relatively shallow, this fret mark was not modelled. As a conservative estimate, the fret mark was assumed to be infinitely long and a two dimensional model was used. Furthermore, a range of notch root radii were examined to determine the effect of root radius. The results of the finite element analyses were incorporated in the flaw evaluation by D.A. Scarth.

Burst Testing of Pressure Tubes Containing Surface Cracks

This is a COG-funded project to develop test methods for fracture toughness testing of tubes containing surface cracks and to investigate the criteria for wall penetration by surface cracks growing by DHC.

The results of a test in which an inside surface flaw in a tube was propagated by DHC until leakage were reported in the COG progress report for September, 1989. A great deal of useful information, including crack velocities and leak rates were obtained from this test. Although the notch geometry prevented crack mouth opening displacement (CMOD) measurements, subsequent fractography indicated that the final ligament size was consistent with the predictions of Prof. E. Smith's model for ductile ligament rupture.

In light of this test, certain improvements have been made to the test control and data acquisition system. Specifically, it was found that the potential drop calibration developed earlier to monitor the depth of external flaws underestimated the depth of the internal flaw. It is postulated that this may be a result of conductance between the crack faces through the pressurizing water. The test data was used to develop a new calibration function for use with internal flaws. At the same time other test data was used to revise the function for external surface flaws. The new functions are more general and give the absolute flaw size rather than just the change and appear to be more accurate at higher crack depths. The functions have the following form:

$$a = (t/k)[\ln(f(V)) - C1]$$

where:

a	= flaw depth at the probe location (mm)
t	= tube wall thickness (mm)
C1	= -1.25(a/t)o
k	= 1 + 1/x (external flaws)
k	= 1 + 1/(4x) (internal flaws)
x	= p.d. probe separation across flaw mouth (mm).
f(V)	= normalized potential drop

Other improvements have also been made to the testing system. It is now possible to implement full closed-loop control during fatigue precracking. The system now has an automatic strain gauge measurement system. Up to 14 channels of conditioned strain output can be acquired during a test. Finally, an optical system for obtaining real time measurements of CMOD has been developed. The resolution of this system should be about 3-4 microns. This system will prevent costly damage to clip gauges used in the past.

A second DHC test is in preparation and will be conducted in January, 1990. This test will contain an external surface flaw and will simulate mid-channel conditions.

In addition to the tube tests, a number of small specimen tests are planned to examine wall penetration and ligament failure in more detail. Preparations for these tests, which will utilize a curved centre cracked test specimen, are nearing completion with the first test expected to be performed in January, 1990. This test will be conducted on a specimen fabricated from the tube used for the DHC test conducted earlier. The small specimen has the same notch size and configuration as the tube test. The result should indicate how well small specimens can be used to investigate the parameters affecting ligament rupture and crack penetration in tubes. If the behaviour is significantly different the small specimen tests may be discontinued.

Effects of Hydride Morphology on Zr-2.5Nb Fracture Toughness

This is a COG-funded project to determine the effects of variations in hydride structure and hydrogen concentration on the fracture toughness of irradiated and unirradiated Zr-2.5Nb.

Three materials have been prepared for this project having hydrogen concentrations of 50, 80 and 200 mg/kg hydrogen. These materials should have nominally similar values of the Hydride Continuity Coefficient (HCC), although this has not yet been measured. Test specimens were prepared for two irradiation periods in NRU. The first canister has been removed and fracture toughness testing at CRNL should commence shortly. Tensile tests are complete. The second canister will remain in NRU throughout 1990.

Testing of unirradiated control specimens at both CRNL and OHRD has essentially been completed. J-R curves from both laboratories generally show good agreement. The behaviour of all 3 materials were quite similar. The material containing 80mg/kg showed a wider range of toughness in the transition region at 175°C. This suggests that this material may contain more radial hydrides than the others.

No metallography or fractography has been conducted yet. However, the fracture surfaces of the 200mg/kg material are distinctly different from the others. This material has a very rough surface charcterized by deep fissures and ridges running parallel to the crack propagation direction. Crack fronts are very uneven with long spikes of crack growth following the fissures. These features are characteristic of large quantities of circumferential hydrides.

Thus although the J-R curves do not indicate large differences in toughness between the three materials, their fracture behaviour does vary significantly.

2.3 Plant Materials

Fracture Toughness of A106B at -196°C

Fracture toughness tests were performed on samples prepared from a 2.5" Sch 100 A106B feeder pipe at both room temperature and liquid nitrogen temperature (-196°C). This pipe had previously been subjected to ice plugging tests in an effort to propagate some intentional weld defects. K_{IC} at -196°C was found to be about 22 MPa $\sqrt{m}$ in both the longitudinal and circumferential directions. This is a considerably higher toughness than the value of 13 measured on a similar pipe in the previous year.

Tests at room temperature gave fairly typical results for this material, with significantly higher toughness in the circumferential direction.

This work will continue in 1990.

Fracture Toughness of Cr-Mo Reheater Tube

As part of the investigation into the failure of a reheater tube at the Thunder Bay TGS, fracture toughness tests were performed on both the failed tube and a similar pre-service tube. Although valid toughness measurements could not be obtained, it was apparent that the failed tube had suffered some degradation in toughness during service. It is not known whether a similar difference would exist at the service temperature.

Hydriding Zr-2.5Nb in a Molten Salt Bath

Work has been ongoing to develop a technique for adding hydrogen to samples of Zr-Nb pressure tube by hydrolysis of a molten bath of KOH and NaOH. The technique is required to prepare samples of material for experiments. Preliminary tests were performed using small samples to prove the technique and investigate the most suitable parameters. It was found that large amounts of hydrogen could be added in a relatively short time.

Work then shifted to adding hydrogen to larger rings of pressure tube and longer tube sections. Preliminary results have shown that the conditions that were found suitable for small specimens are less effective for larger pressure tube pieces. The reasons for this are presently unclear. Part of the problem may be that the large samples are only hydrided from one surface while the small specimens were hydrided on all sides. Experiments are continuing and will investigate the additions of arsenic and moisture to the bath. These factors were not found to make a consistent difference with the small specimens but may be helpful for increasing hydrogen uptake with larger samples.

Fracture Properties of Heavy Water Plant Blistered Steel

The fracture properties of hydrogen-blistered steel were evaluated to assist in establishing repair or retirement criteria for hydrogen blistered pressure vessels at BHWP. Fracture toughness tests were performed on unblistered and blistered steel at 21 and 43°C. Results indicated that blisters appeared to have little effect on the material's crack growth resistance. Hydrogen had a marked effect on toughness, reducing the crack growth resistance of hydrogen-charged material threefold at 21°C. Differences in fracture toughness were also reflected in the mode of fracture of the hydrogen-charged and uncharged steel. The fracture surfaces of the charged steel exhibited quasi-cleavage, while the uncharged steel showed normal dimple rupture.

As a first step in establishing retirement criteria for the blistered pressure vessels an analysis was carried out to determine the critical crack length of a postulated axial through-wall defect in the bottom section of H_2S absorber tower DA-3110. A critical crack size of 203 mm was calculated using lower bound material properties and current proposed ASME code safety factors.

Fracture Properties of A212 Gr B Steel

A test program was carried out to characterize the fracture properties of A212 Gr B steel base metal and weld metal that have been in service at Lakeview TGS. Material for this program was obtained from sections of downcomers from Units 5, 7 and 8 of Lakeview TGS.

Tensile and fracture toughness tests were conducted on the base metal and weld metal. In addition, dropweight and Charpy impact tests were carried out on the base metal. The fracture toughness tests were carried out at 21, 250 and 366°C. The intermediate temperature of 250°C was selected because lower material fracture properties may occur at this temperature from dynamic strain aging. A number of weld metals were metallographically examined, and base and weld metal fracture surfaces were also examined by scanning electron microscopy.

Results indicated that the parent metals exhibited the lowest fracture toughness at 218°C. The submerged arc welds (SAW) exhibited an intermediate level of crack growth resistance while the shielded metal arc welds (SMAW) showed the highest crack growth resistance. Lower crack growth resistance was exhibited at 250°C for nearly all the base and weld metals tested than at 21 and 366°C. The reduced fracture properties at 250°C was attributed to dynamic strain aging.

2.4 Flaw Assessments

Fitness for Service Evaluation of Flaws in Zr-Nb Pressure Tube

A PC program for flaw evaluations in Zr-Nb pressure tubes is under development. This PC program is based on the technical specifications being written by D. Scarth. As a result of the modifications to the technical specifications that are being made currently, the program development is temporarily put on hold until the modifications are finished.

Rolled Joint Residual Stress

A draft of the summary report of the various rolled joint residual stress research programs conducted by AECL and CGE is in the finishing stage and should be ready to send out for comment. This summary will only include experimental measurements that are applicable to Ontario Hydro CANDU nuclear generating stations. The final report could be used as a reference in flaw evaluation.

Numerical simulations of the rolling process were conducted. Due to limitations of the finite element code ABAQUS, only reasonable agreement was achieved with experimental measurements by AECL for the over-extended joints (Pickering Units 3 and 4).

2.5 1990 Work Plan

Several issues have arisen during the development of the proposed Fitness-for-Service guidelines for Zr-Nb pressure tubes. These include the calculation of the Critical Crack Length (CCL) from J-R curves taken from small specimens, the length at through-wall crack penetration of a crack growing by Delayed Hydride Cracking (DHC) in the bulk of the pressure tube, and the application of probabilistic fracture mechanics to predicting the structural integrity of pressure tubes. The proposed work in numerical fracture mechanics will be focussed to address these issues.

The crack driving force elastic-plastic J-integral would be calculated by three-dimensional finite element analysis as a function of internal pressure for several lengths of through-the-wall cracks in pressure tubes. Results will be compared with formulae currently in use. The elastic-plastic J-integral for the non-standard compact tension specimen would be calculated numerically. Results would be compared with standard ASTM formulae currently in use.

It is proposed to study DHC initiation from an applied mechanics view point. The local stress/strain fields surrounding the notch tip in both the notched experimental test specimens and postulated blunt surface flaws in pressure tubes would be calculated. Results will be compared to quan-

tify conservatisms in the current blunt surface flaw evaluation methodology. A second phase of the study will investigate the crack tunnelling behaviour and final ligament collapse from an applied mechanics viewpoint. A framework for performing the probabilistic risk assessment of crack initiation in pressure tubes will be developed. The proposed work would be performed in cooperation with WNRE to ensure that consistent objectives are being met with no redundancy in effort.

Structural integrity evaluation of nuclear and thermal plant components will be conducted, if and when they are required. Assistance will be provided to CPS staff members to conduct and review flaw evaluation reports for submission to AECB. Work will continue on the development of computer programs to transfer flaw evaluation technologies to CPS.

In experimental fracture mechanics, fracture testing of pressure tube samples containing surface cracks will continue in a COG funded program. The mechanics of ligament failure leading to the penetration of surface cracks will be examined using burst specimens and small curved centre-cracked specimens. Flaws of different sizes will be propagated by DHC until leakage or instability. The influence of end fitting constraint in wall penetration will also be studied. Effects of variations in hydride structure and hydrogen concentration on the fracture toughness of irradiated and unirradiated Zr-2.5% Nb will also continue. Work in 1990 will consist of administering CRNL test on irradiated specimens and the preparation and testing of material containing mixed hydrides at higher concentrations. Small specimen test results will also be checked against burst specimen tests.

Work will continue on determining the effect of a simulated CANDU environment on the fatigue crack growth rate of unirradiated pressure tube material. The effect of low and high dissolved oxygen concentrations will be examined. A second autoclave test facility is also being commissioned for fatigue testing in a water environment.

Several projects are also planned for materials used in the balance of the plant. Cryogenic fracture toughness of SA106B 12" Sch 100 piping steel are planned to determine fracture toughness at liquid nitrogen temperature. These tests are part of a large program sponsored by CPS aimed at avoiding failure during ice plugging. Material tests will be conducted on a low sulphur steel as a part of an ongoing program to assess a shear punch test method for estimating a material's fracture toughness.

III - SUPPORT TO THE EXTERNAL COMMUNITY

External Activities

(i) ASME Section XI Flaw Evaluation Working Group Activities

The FM Unit is continuing to keep abreast with developments in flaw evaluation procedures for Section XI of the ASME Boiler and Pressure Vessel Code. A member of the Unit is participating in Section XI meetings and development of Code procedures.

(ii) **Research Project to Develop Shallow Crack Fracture Mechanics Tests**

Ontario Hydro is a sponsor of an international research project to develop shallow crack fracture mechanics tests. This project is being carried out at The Welding Institute (Cambridge, UK) and the Edison Welding Institute (Columbus, Ohio). The FM Unit is Ontario Hydro's representative for this project, while the sponsor's fee is provided by the Chemistry and Metallurgy Department of CPS.

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